Physical modelling applied to infrastructure development

R.J. Goodey
City, University of London, London, UK

ABSTRACT: The physical modelling conference series has served as a primary means of sharing practise and disseminating current research in experimental geotechnics. Each conference highlights the trends, techniques and direction of current research. This paper summarises contributions to the 9th International Conference on Physical Modelling in Geotechnics from researchers broadly in the field of infrastructure development. This themed paper aims to identify innovative approaches to geotechnical problems, advances in experimental techniques and equipment in order to address new research questions and future trends in infrastructure research that might feature more significantly in future conferences. Some reflection on past conference proceedings is included with the hope that the community appreciates the scale of our achievements since the first conference in the series.

1 INTRODUCTION

Now in its ninth iteration, the International Conference on Physical Modelling in Geotechnics is the pre-eminent forum for the dissemination of research in all areas related to experimental geotechnics. From the early days, the conference series has grown and matured and this is reflected in the contributions submitted from researchers which have increased both in number as well as in complexity of topics addressed and range of techniques adopted.

The aim of this paper and the accompanying lecture is to highlight some of the contributions and advances made in the area of infrastructure development. Within this field there are many areas of interest and this is reflected in the high number of papers submitted to the conference. These papers detail work carried out using a wide variety of experimental techniques including large scale testing, centrifuge modelling and comparisons with field data.

The organisation of this paper follows the broad theme of the papers with the aim of identifying advances in the field as well as highlighting areas of future interest.

2 URBAN DEVELOPMENT

In urban areas there is a high demand to maximise available land and other resources. This has led to taller buildings with larger foundations and deeper basements. These types of structure can be difficult to construct in urban environments, there can be issues of noise during construction, interaction with existing infrastructure, as well as the need to ensure protection from earthquakes and other natural events. There are also problems of increasing subsurface congestion on new construction i.e. as buildings are redeveloped there are existing piles to consider as well as the need to avoid damage to existing infrastructure.

2.1 *Driven piles*

Conventional installation methods for driven piles (i.e. impact or vibration driving) cause undesirable noise and vibration in urban environments. One solution investigated by El Haffar et al. (2018) and Frick et al. (2018) is to use rotary jacked piles whose installation is much lower in both noise and vibration. These studies use coarse grained soils and investigate the influence of the installation parameters (forces and jacking stroke). Both studies produce broadly similar conclusions in that the installation forces and final capacity of the piles are strongly linked to the installation method adopted.

2.2 *Deep basements*

Deng & Haigh (2018) and Chan & Madabhushi (2018) both present preliminary work relating to deep basements. These papers investigate more efficient basement design (recognising that urban development now routinely incorporates deep basements) and both studies aim to investigate the underlying mechanisms. Deng & Haigh (2018) describe experimental work on soil movements behind a retaining wall. In this work, the wall movements are controlled and DIC (Digital Image Correlation, e.g. White et al. 2003) is used to monitor the soil response. This approach has been adopted as a more fundamental investigation of movements around excavations when compared with existing guidance (e.g. Clough & O'Rourke 1990) which is often based on empirical data and may not be universally applicable. Chan & Madabhushi (2018) also present work under development but here focussing on the heave behaviour of basement slabs founded on overconsolidated clay. The aim of the work is to study the influence of slab and basement stiffness on heave whereas previous work has focussed on specific cases or mitigation techniques. The results presented, whilst at an early stage, highlight not only the potential outcomes of the project, but also the complexity of the centrifuge modelling being carried out currently and the difficulties encountered.

3 ROADS AND PAVEMENTS

In the area of transportation infrastructure it is interesting to note that the majority of papers submitted to the conference are concerned with maintenance and prediction of long term performance. This is understandable given that many countries have well developed transport systems, elements of which may have originally been constructed more than a century ago.

3.1 *Pipelines buried beneath roads*

For ease of installation and maintenance, utility pipes are often buried beneath roads. This results in shallow pipelines which are subjected to significant cyclic loads from above. Bayton et al. (2018) report centrifuge tests of model pipelines subjected to simulated traffic loads. The motivation for the study is to minimise leakage from pipe networks with water supplies being highlighted. The work concentrates on the accumulation of bending moment within the pipe with repeated load cycles which could eventually result in damage to the pipe causing subsequent leakage. The effects of that leakage in the form of development of sinkholes are investigated in other papers (Kuwano et al. 2018, Indiketiya et al. 2018, Kearsley et al. 2018). Both Kuwano et al. (2018) and Indiketiya et al. (2018) use 1g testing and DIC to investigate the formation and propagation of a void above a simulated pipe with a defect. The experiments simulate the situation where soil is washed into the pipeline via the defect. It is interesting to note that in all cases very little movement is observed at the ground surface before the cavity collapses. The experimental arrangements in these papers are similar and in all cases soil below the water table is more prone to development of a cavity (as it is washed into the pipe via the defect). Indiketiya et al. (2018) conclude that cavity development is a function of the soil size when compared with the pipe defect but that it is difficult to identify a relationship between volume of soil lost and the size of the defect in the pipe. Kuwano et al. (2018) draw a similar conclusion with respect to the ratio of defect versus soil grain size but, due to the pipe defect having a fixed size in this study, do not comment on this aspect.

Laporte et al. (2018) report the development of apparatus to investigate the effect of wetting and drying cycles on expansive soils. Differential soil displacements can result in cracked pavements, damage to buried pipes and foundation movements. The experimental arrangement incorporates a model pavement and associated drainage ditch. This work shows significant differential movements between areas exposed directly to the elements and those shielded by the pavement surface. Again the work presented highlights the level of technical complexity that is being achieved in centrifuge modelling as well as the precise measurements that can be made via conventional instrumentation and DIC.

3.2 *Pavement design*

Two papers (Smit et al. 2018a,b) detail experimental investigations of Ultra-Thin Continuously Reinforced Concrete Pavement. This is proposed as a cost effective alternative to traditionally designed pavements and comprises a thin layer of heavily reinforced concrete. These papers highlight the problems associated with applying conventional design approaches to this innovative pavement design. The authors rightly highlight differences in design approach that would need to be accounted for given the observed difference in behaviour between this and traditional pavements.

4 PILES AND PILED FOUNDATIONS

Piled foundations are utilised in a wide range of applications; as foundations for medium to large size structures (both in isolation and as part of a piled raft), reinforcement under embankments or existing structures, to form walls and, more recently, as energy piles. This wide range of applications is reflected in the significant number of papers relating to pile performance. There is a particular focus on seismic and cyclic performance with the majority of the studies using centrifuge modelling techniques although 1g and shaking table tests are also utilised.

4.1 *Piles under seismic action*

A number of papers investigate the performance of piles under seismic loading. The experiments consider single piles (Yao et al. 2018, Ebeido et al. 2018, Chen et al. 2018, Pérez-Herreros et al. 2018) or small pile groups (Imamura 2018, Egawa et al. 2018). One paper (Garala & Madabhushi 2018) considered a comparison between a single pile and a small pile group (containing three piles). A range of soil conditions are used although sands and coarse grained soils are predominant. The majority of the papers investigate pile response in terms of bending moments and pile movements.

Many studies apply seismic loading either utilising input motion recorded during real earthquakes (e.g. Pérez-Herreros et al. 2018) or idealised sinusoidal motion, however Yao et al. (2018) have created an experimental apparatus to directly model the movement of a fault and used this to investigate the effect this has on piles close to and within the fault zone. This work also uses laser displacement transducers to measure the movement of the pile head and presents a good comparison between these measurements and those obtained from DIC. Significant bending moments and movements are observed in all piles, even those some distance from the fault zone. The authors conclude that, as in the real case, piles within the fault zone would most likely be completely sheared.

Egawa et al. (2018) present a series of tests on piles within layered soil models. The soils used are sand and volcanic ash and a variety of arrangements were tested (with respect to number and thickness of each layer). Despite the variation in test arrangements it was shown that large bending moments were consistently produced in the piles at around mid-height. It would be interesting to investigate whether this observation was repeated with different arrangements or sizes of pile. Pérez-Herreros et al. (2018) also use layered soil samples in their experiments on pile response, in this case the model is overconsolidated clay overlying dense sand. The model pile is predominantly embedded within the clay with its base just penetrating the sand layer beneath. Of great interest in this work is the observation that bending moments in the pile are strongly influenced by the amount of embedment into the dense sand layer. This obviously has great significance in areas where soft soils overly sands and end-bearing piles might be used.

4.2 *Static behaviour of piles and piled foundations*

Bisht et al. (2018) and Rodríguez et al. (2018) both present work investigating the performance of piled raft foundations. Bisht et al. (2018) show how the total load capacity is affected by the arrangement of piles the lengths of each pile within the group. A better understanding of how piles within the raft interact and contribute to the overall capacity could lead to more efficient designs. Rodríguez et al. (2018) concentrate on how the piled raft performs during changes of pore water pressures. These changes could arise from consolidation processes or by pumping from deep aquifers which is common in many cities. The authors present their results in terms of proportion of load carried by the raft or the piles. As pore water pressures decrease the proportion of load carried by the piles increases significantly, accompanied by a separation of the soil from the underside of the raft. This would have an impact on the design of both the piles and the raft although, as Bisht et al. (2018) point out, the contribution of the raft is often ignored in conventional design even though that implies poor economy.

Panchal et al. (2018) present a small study on a hybrid foundation system combining sheet piles with a pile cap. The aim is to produce a sustainable foundation design that can be used in already heavily developed urban areas. This type of foundation could be easily removed and recycled in the future which is not possible when dealing with bored, cast in-situ piles that are often found during site redevelopment. The results show a strong influence of geometry on the load capacity but that easily constructed square sheet pile groups could be a viable alternative to traditional bored piles.

4.3 *Energy piles*

Two papers highlight how physical modelling can be applied to new and emerging technologies. Energy piles combine structural requirements with the thermal performance of a ground source heat pump. The challenge is to assess the influence of the temperature changes on the structural performance. In a clay soil temperature changes will generally result in pore pressure variations due to the low permeability of the clay. The resulting change in effective stress is presumed to affect the interaction between soil and pile. Parchment & Shepley (2018) present a fundamental study of the influence of temperature on a soil-structure interface. A large number of direct shear tests between clay and a structural element (an aluminium block) are carried out. The study concludes that, for the rnage of temperatures that might be expected in a thermal pile, there is little effect in overconsolidated clay. Any effects seen relate to adhesion between pile and soil and may, in fact, be structurally beneficial. In normally consolidated clays the effect of heating is negligible.

Ghaaowd et al. (2018) present work on how heating affects the properties (undrained strength) of a clay sample and the resulting effect on pullout strength of a heated versus unheated pile. Significant increases in the pullout capacity are observed after heating. Only one (extended) cycle of heat was applied and it would be interesting to investigate how cycles of the type that would be expected in a thermal pile influenced the soil and pile behaviour.

5 SLOPES AND EMBANKMENTS

Slopes (both engineered and natural) present potential hazards primarily related to their long term performance and stability. A significant number of the papers submitted in this area deal with assessing and predicting the response of a slope to changes in pore water. The slopes studied are generally clay or clay dominated.

5.1 *Slopes subjected to wetting and drying*

Slopes and embankments are generally subjected to cyclic variation of wetting and drying. This could be due to seasonal variation, tidal variation or changes in reservoir level amongst other phenomena. Ahmed et al. (2018) present work investigating the movement of a slope subject to cyclic variation representative of tidal cycles. Similarly, Luo & Zhang (2018) simulated more extreme variations of wetting and drying more representative of the changing levels in a reservoir. Both of these studies adopted a similar, centrifuge based, approach and used DIC to monitor the movements. Movements are shown to accumulate with increasing numbers of cycles which obviously has implications for the long term stability of the slope. Ahmed et al. (2018) also carried out in-flight measurements of the soil strength within the slope and demonstrated that strength changed quite significantly with only a relatively small number of cycles. Again, this has implications for the long term stability of the slope.

Variations in water content can also be affected by vegetation on the slope. Vegetation is often cleared from embankments near roads and railway lines in order to reduce the potential for accidents and disruption. The effect of vegetation removal is investigated by Kamcoom & Leung (2018). These effects are twofold; firstly, removal of the vegetation would halt transpiration, potentially increasing pore water pressures in the embankment and secondly, the live roots act like reinforcement, the effectiveness of which will be reduced as the root decays. Kamcoom & Leung (2018) create a centrifuge model of a slope with artificial roots connected to a vacuum system. In this way, plant transpiration can be simulated and, by control of the suction from the artificial roots, plant removal can also be simulated. The results of these tests show that removal of plants from the upper portions of the slope has minimal effect on slope stability but stability is significantly compromised when vegetation is removed from the lower portion of the slope.

As well as fluctuations that might be interpreted as relatively easy to predict, if not account for, slopes and embankments are often subject to flooding. Saran and Viswanadham (2018) detail centrifuge tests on model levees which are subjected to flood events. Given that the potential for catastrophic failures to occur is well recognised and documented (e.g. Steedman & Sharp 2011) this work is significant and timely. Saran and Viswanadham (2018) perform centrifuge tests comparing the efficiency of horizontal and vertical (chimney) drainage layers within the levee. The experimental work is compared with numerical models. The experimental results suggest that the chimney drain increases the stability of the levee more effectively than the horizontal drain. This conclusion is not necessarily borne out by the numerical model which suggests that either drainage system results in a similar factor of safety against failure.

5.2 *Embankments on soft soils*

The problem of constructing an embankment over regions of soft soils is addressed by a number of papers. Founding an embankment on a soft underlying layer will generally result in long term settlements as the soft soil consolidates under the embankment load potentially damaging road and rail infrastructure. One solution to this problem is to improve the soft soil layer prior to embankment construction for which there are a number of approaches. Shiraga et al. (2018) detail centrifuge experiments on an embankment constructed using vacuum consolidation. Comparisons are made between embankment construction on the soft layer with and without the vacuum consolidation process. The results indicate that the vacuum consolidation process returns the pore water pressures in the ground to their original levels more quickly than simple embankment construction alone. Careful construction sequencing using this technique could reduce the possibility of having to undertake remedial works by ensuring settlements are mostly complete prior to installation of infrastructure on the embankment.

Another technique is to construct a piled embankment. The aim of this method is to reduce the load applied to the surface of the soft soil layer. This can be achieved by use of a geosynthetic such that the load spans between the piles beneath the embankment. Almeida et al. (2018) carried out multiple centrifuge experiments to investigate the influence on embankment performance of number geosynthetic layers, geosynthetic pretension, and pile size and arrangement. Their results concluded that use of a geosynthetic layer was extremely efficient in transferring load to the piles but there was no benefit to multiple layers and that the pretensioning effect was minimal. Blanc et al. (2018) also investigated the load transfer from the embankment (or granular mattress) to the piles below the embankment. In this work there was no geosynthetic reinforcement and only the pile spacing, size and height of embankment was varied. The work was carried out with the aim of validating previously published analytical models although the results suggest that each model is capable of representing some features of the system better than others.

6 TUNNELS AND PIPELINES

In previous conferences in this series, research and experimentation into tunnelling has been particularly well represented. It is interesting to note that for the 9th ICPMG the number of papers in this field is limited, perhaps indicating that researchers are adopting other techniques in this area.

6.1 *Tunnelling*

Tunnels are generally used in urban areas for mass transit systems. This is generally because of surface space constraints. Once constructed, tunnels can be subject to a variety of load conditions. Hajialilue-Bonab et al. (2018) describe 1g shaking table tests on an instrumented tunnel representative of a section of the Tabriz subway. Historically, underground structures have been subjected to lower levels of damage during earthquakes although the work presented here indicates that there may be a significant effect, particularly in strong ground shaking events. De & Zimmie (2018) investigated the effect of surface explosions on a tunnel. Measurements are presented on the basis of additional strains imparted to the tunnel lining during the event and some techniques for mitigation are investigated. The test arrangements are all shallow tunnels and it might be inferred that deeper cover (although not always possible) would result in more attenuation of the energy imparted by the explosion.

Xu & Bezuijen (2018) investigate the tunnelling construction process, specifically use of bentonite slurry to support the tunnel face during shield tunnelling. This is a 1g element testing study of how the bentonite filter cake develops as pore fluid infiltrates the soil surrounding the tunnel cavity. It was shown that different concentrations of bentonite affect the permeability of the surrounding soil with an almost direct relationship. The quantification of this would be useful information when designing tunnelling schemes through sandy strata.

6.2 *Pipelines*

Pipelines are used both onshore and offshore for the distribution of, for example, oil and gas. Extremely long networks are vulnerable to many hazards as they may cross earthquake zones, faults, slopes and many different soil conditions. Eichhorn & Haigh (2018) use the mini-drum centrifuge to examine the uplift resistance of pipes positioned parallel to the fall of a slope. Careful consideration is given to the scaling of the pipe model such that it is representative of a high pressure transmission pipeline that is currently in use. The experiments highlight deficiencies in the current methods used by industry.

The resistance to uplift is of critical importance during earthquakes or when large ground movements occur such as in a landslide. Wang et al. (2018) present a novel solution to the problem of uplift during earthquakes which is to strengthen the soil overlying the pipeline with vegetation. Model plant roots were created using a 3D printer and used to strengthen the soil in the upper layer of their experimental model. Results were presented in terms of the relative uplift of the pipeline with respect to the ground under the action of three earthquakes varying in intensity. Compared with a baseline case were there was no reinforcement, the introduction of roots to the soil did reduce pipeline uplift. The magnitude of reduction was related to the size of the roots. It was noted that uplift forces did not appear to be reduced and therefore the reduction was attributed to the increase in soil strength obtained from the root systems.

7 RETAINING WALLS

Retaining walls are found in a wide range of engineering projects including basement construction, retained embankments, and quays. There are also a wide variety of construction methods and materials. This diversity of application is represented by a number of papers investigating a range of topics including sheet piles, nailed walls and earth walls.

7.1 *Earth walls*

Walls constructed from earth offer advantages over other wall types such as low cost and ease of construction. To ensure stability, earth walls must contain some element of reinforcement and these systems are variously referred to as Geosynthetic Reinforced Soil Walls, Mechanically Stabilised Earth Walls and Reinforced Earth Walls. The performance of these types of walls relies on the interaction between the soil and the reinforcing elements. Mirmoradi & Ehrlich (2018) report large scale experiments on two Geosynthetic Reinforced Soil walls. Each wall was similar in design however one was faced with blocks and the other faced by wrapping the geosynthetic fabric around the soil. The wrap-faced wall was overall more flexible and transferred more of the applied surcharge load into the geosynthetic reinforcement. It is inferred that, given the good performance of both wall types, that the wrap-faced wall may be a preferred design solution on the basis of cost.

As stated earlier, the behaviour (and analysis) of these types of wall is dependent on the interaction between reinforcement and soil. Loli et al. (2018) have presented a large scale device for testing (and therefore characterising) reinforcement buried within soil. This device allows control of the overburden stress and is of a size sufficient to test many types of reinforcement. The performance of the device is compared with numerical modelling and the design choices justified on this basis. Whilst the focus of the paper is the device itself, it is clear that better understanding of the interaction between soil and reinforcement will enable more efficient and economical earth wall designs.

7.2 *Soil-nailed walls*

Two papers from the same group investigate walls reinforced with soil nails. Sabermahani et al. (2018) investigate the optimal arrangement of nails within an irregularly shaped excavation whereas Akoochakian et al. (2018) consider a more regular, rectangular excavation. The motivation for both these pieces of work relates to maximisation of available space during urban development. The work presented in both of these papers highlights that, even in relatively simple cases of regularly shaped excavations, the spacing of the nails, stiffness of the wall facing and presence of surcharge behind the wall all greatly influence the movements observed around the excavation.

8 SHALLOW FOUNDATIONS

As highlighted in the section described the papers submitted in the area of tunnels and pipelines, it is interesting to note how research activity changes over the years. In earlier iterations of the ICPMG there were many papers concerning the behaviour of shallow foundations but this number is very much reduced for the 9th ICPMG.

Qi & Knappett (2018) and Ghalandarzadeh & Ashtiani (2018) both present work relating to the response of shallow foundations under seismic loading. In the paper of Ghalandarzadeh & Ashtiani (2018) a similar approach to that taken by Yao et al. (2018) is adopted whereby an apparatus is developed that induces a predefined fault plane into the soil model and the response of the foundation to this is monitored. The footing load was generally maintained constant with embedment and distance from the fault plane being varied. Results are presented in terms of footing rotation. In general, footings founded on the surface experience less rotation compared with footings that are initially embedded. The magnitude of the footing load appears to have little effect upon this result. As with Yao et al. (2018) the zone of influence of the fault is quite large so foundations are affected wherever they are placed within the experiment.

Qi & Knappett (2018) investigate the influence of soil permeability on shallow foundations (supporting a low-rise structure). The time histories of real earthquakes were applied sequentially. The results showed that, even if the potential for liquefaction could be identified, the prediction of structural damage is extremely difficult to estimate. In particular the effect of strong aftershocks seemed to place higher demands on the structure whilst not necessarily resulting in significant additional settlement or rotation.

9 GROUND IMPROVEMENT

There are many techniques available for ground improvement. The term generally refers to increasing soil strength but may also refer to the improvement of drainage. A number of papers submitted have considered ground improvement as a means to mitigating the effects of earthquakes. In particular, the use of drains (of various types) as mitigation against the effects of liquefaction is the subject of several papers. Paramasivam et al. (2018), García-Torres et al. (2018), Marques et al. (2018) and Kirkwood & Dashti (2018) all consider the use of vertical drains whilst Apostolou et al. (2018) consider the use of stone columns although their tests did not represent structural loads but rather, investigated dissipation of excess pore water pressures within the soil model. Finally, although not strictly speaking a ground improvement technique, Nigorikawa et al. (2018) describe a base isolation system as a mechanism to mitigate liquefaction effects.

All of these studies utilise centrifuge modelling techniques, highlighting the applicability of this method to studying earthquake related problems. The four papers that considered vertical drains underneath model structures (Paramasivam et al. 2018, García-Torres et al. 2018, Marques et al. 2018 and Kirkwood & Dashti 2018) all demonstrate a reduction in earthquake induced rotation and settlements when drains were used. There appeared to be a cost associated with this improvement however, in terms of the motion transferred to the superstructure. Both Kirkwood & Dashti (2018) and Paramasivam et al. (2018) saw increased accelerations of the structure when mitigation by drains was included. Additionally, in the tests of Kirkwood & Dashti (2018) an adjacent structure without drains was present which experienced an increase in rotations. The implication here is that this solution would either need to be applied to all structures in an area or that some sort of isolation or cut-off wall would be required to protect unmitigated structures.

10 SUMMARY AND CONCLUSION

Approximately fifty papers submitted to the 9th ICPMG have been reviewed in order reflect upon the contributions made, both in terms of experimental techniques being adopted and research questions currently being addressed. These contributions have been discussed with a view to identifying future trends and research questions whilst keeping in mind the progress that has been exhibited in the field over the entire conference series.

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